CHAPTER 3.—GAGING-STATION CONTROLS

TYPES OF CONTROL

The conversion of a record of stage to a record of discharge is made by the use of a stage-discharge relation. The physical element or combination of elements that controls the relation is known as a control. The major classification of controls differentiates between section controls and channel controls. Another classification differentiates between natural and artificial controls. (Artificial controls are structures built for the specific purpose of controlling the stage-discharge relation; a highway bridge or paved floodway channel that serves incidentally as a control is not classed as an artificial control.) A third classification differentiates between complete, partial, and compound controls.

Section control exists when the geometry of a single cross section a short distance downstream from the gage is such as to constrict the channel, or when a downward break in bed slope occurs at the cross section. The constriction may result from a local rise in the streambed, as at a natural riffle or rock ledge outcrop, or at a constructed weir or dam; or it may result from a local constriction in width, which may occur naturally or be caused by some manmade channel encroachment, such as a bridge whose waterway opening is considerably narrower than the width of the natural channel. Examples of a downward break in bed slope are the head of a cascade or the brink of a falls.

Channel control exists when the geometry and roughness of a long reach of channel downstream from the gaging station are the elements that control the relation between stage and discharge. The length of channel that is effective as a control increases with discharge. Generally speaking, the flatter the stream gradient, the longer the reach of channel control.

A complete control is one that governs the stage-discharge relation throughout the entire range of stage experienced at the gaging station. More commonly, however, no single control is effective for the entire range of stage, and so the result is a compound control for the gaging station. A common example of a compound control is the situation where a section control is the control for low stages and channel control is effective at high stages. The compound control sometimes includes two section controls, as well as channel control. In that situation the upstream section control is effective for the very low stages, a section control farther downstream is effective for intermediate stages, and channel control is effective at the high stages.

With regard to complete controls, a section control may be a complete control if the section control is a weir, dam, cascade, or falls of such height that it does not become submerged at high discharges. A channel control may be a complete control if a section control is absent, as in a sand channel that is free of riffles or bars, or in an artificial channel such as a concrete-lined floodway.

A partial control is a control that acts in concert with another control in governing the stage-discharge relation. That situation exists over a limited range in stage whenever a compound control is present. As an example consider the common situation where a section control is the sole control for low stages and channel control is solely operative at high stages. At intermediate stages there is a transition from one control to the other, during which time submergence is "drowning out" the section control. During that transition period the two controls act in concert, each as a partial control. In effect we have a dam (low-flow control) being submerged by tailwater; before complete submergence (channel control), the upstream stage for the particular discharge is dependent both on the elevation of the dam and on the tailwater elevation. Where the compound control includes two section controls, the degree of submergence of the upstream section control will be governed by the downstream section control, during a limited range in stage. When that occurs, each of the section controls is acting as a partial control. A constriction in channel width, unless unusually severe, usually acts as a partial control, the upstream stage being affected also by the stage downstream from the constriction.

ATTRIBUTES OF A SATISFACTORY CONTROL

The two attributes of a satisfactory control are permanence (stability) and sensitivity. If the control is stable, the stage-discharge relation will be stable. If the control is subject to change, the stage-discharge relation is likewise subject to change, and frequent discharge measurements are required for the continual recalibration of the stage-discharge relation. That not only increases the operating cost of a gaging station, but results in impairment of the accuracy of the streamflow record.

The primary cause of changes in natural controls is the high velocity associated with high discharge. Of the natural section controls, a rock ledge outcrop will be unaffected by high velocities, but boulder, gravel, and sand-bar riffles are likely to shift, boulder riffles being the most resistant to movement and sand bars the least resistant. Of the natural channel controls those with unstable bed and banks, as found in sand-channel streams, are the most likely to change as a result of velocity-induced scour and deposition.

Another cause of changes in natural controls is vegetal growth. The growth of aquatic vegetation on section controls increases the stage for a given discharge, particularly in the low-flow range. Vegetal growth on the bed and banks of channel controls also affects the stage-discharge relation by reducing velocity and the effective waterway area. In the temperate climates, accumulations of water-logged fallen leaves on section controls each autumn clog the interstices of alluvial riffles and raise the effective elevation of all natural section controls. The first ensuing stream rise of any significance usually clears the control of fallen leaves.

Controls, particularly those for low flow, should be sensitive; that is, a small change in discharge should be reflected by a signficant change in stage. To meet that requirement it is necessary that the width of flow at the control be greatly constricted at low stages. In a natural low-water control such constriction occurs if the control is in effect notched, or if the controlling cross section roughly has a flat V-shape or a flat parabolic shape. Those shapes will ensure that the width of flow over the control decreases as discharge decreases. Generally speaking, a low-water control is considered to be sensitive if a change of no more than 2 percent of the total discharge is represented by a change of one unit of recorded stage. For example, in the U.S.A., stage is recorded in units of hundredths of a foot; therefore, for the low-water control to be regarded as sensitive, a change in stage of 0.01 ft (0.003 m) should represent a change of no more than about 2 percent of the total discharge.

In the interest of economy a gaging station should be located upstream from a suitable natural control (fig. 2). However, where natural conditions do not provide the stability or the sensitivity required, artificial controls should be considered. The artificial controls are all section controls; it is not feasible to pave or otherwise improve a long reach of channel solely for the purpose of stabilizing the stage-discharge relation.

ARTIFICIAL CONTROLS

An artificial control is a structure built in a stream channel to stabilize and constrict the channel at a section, and thereby simplify the procedure of obtaining accurate records of discharge. The artificial controls built in natural streams are usually broad-crested weirs that conform to the general shape and height of the streambed. (The term "broad-crested weir," as used in this manual, refers to any type of weir other than a thin-plate weir.) In canals and drains, where the range of discharge is limited, thin-plate weirs and flumes are the controls commonly built. Thin-plate weirs are built in those channels whose flow is sediment free and whose banks are high enough to accommodate the increase in stage (backwater) caused by the installation of a weir (fig. 3). Flumes are largely self cleaning and can therefore be used in channels whose flow is sediment laden, but their principal advantage in canals and drains is that they cause relatively little backwater (head loss) and can therefore be used in channels whose banks are relatively low. Flumes are generally more costly to build than weirs.

Flumes may be categorized with respect to the flow regime that principally controls the measured stage; that is, a flume is classed as either a critical-flow flume or a supercritical-flow flume. The Parshall flume (fig. 4) is the type of critical-flow flume most widely used. Supercritical-flow flumes are used in streams that transport heavy loads of sediment that include rocks that are too large to pass through a critical-flow flume without being deposited in the structure. Of those flumes the trapezoidal supercritical-flow flume (fig. 5) is the most widely used by the U.S. Geological Survey.

Artificial controls eliminate or alleviate many of the undesirable characteristics of natural section controls. Not only are they physically stable, but they are not subject to the cyclic or progressive growth of aquatic vegetation other than algae. Algal slimes that sometimes form on artificial controls can be removed with a wire brush, and the controls are self cleaning with regard to fallen leaves. In moderately cold climates artificial controls are less likely to be affected by the formation of winter ice than are natural controls. The artificial control can, of course, be designed to attain the degree of sensitivity required for the gaging station. In addition, an artificial

FIGURE 2.—Gage and natural control, Little Spokane River at Elk, Wash.

control may often provide an improved discharge-measurement section upstream from the control by straightening the original angularity of flow lines in that cross section.

In canals or drains, where the range of discharge is limited, artificial controls are usually built to function as complete controls throughout the entire range in stage. In natural channels it is generally impractical to build the control high enough to avoid submergence at high discharges, and the broad-crested weirs that are usually built are effective only for low, or for low and medium, discharges. Figures 6 and 7 illustrate broad-crested weirs of two different shapes; the crests of both have a flat upward slope from the center of the stream to the banks, but in addition, the weir in figure 7 has a shallow V-notch in the center for greater sensitivity.

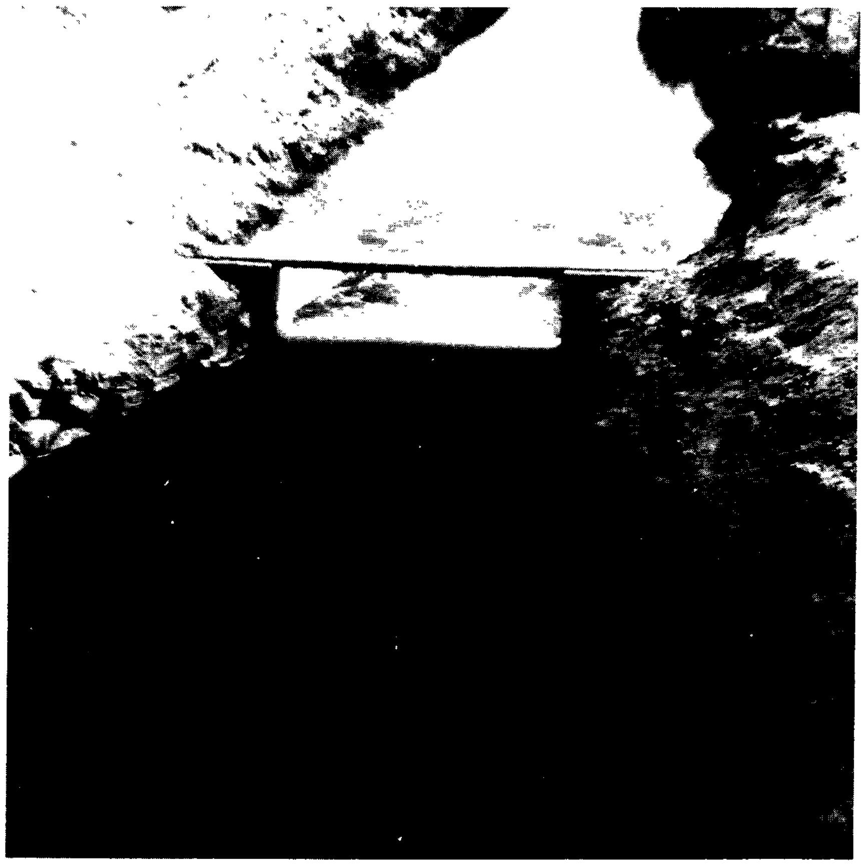

FIGURE 3.—Rectangular weir on Trifolium Drain 23 of Imperial Irrigation District, near Westmorland, Calif. (View looking downstream.)

The attributes desired in an artificial control include the following:

1. The control should have structural stability and should be permanent. The possibility of excessive seepage under and around the control should be considered, and the necessary precautions should be taken for the prevention of seepage by means of sheet piling or concrete cut-off walls and adequate abutments.
2. The crest of the control should be as high as practicable to possibly eliminate the effects of variable downstream conditions or to limit those effects to high stages only.
3. The profile of the crest of the control should be designed so that a small change in discharge at low stages will cause a measurable change in stage. If the control is intended to be effective at all stages, the profile of the crest should be designed to give a stage-discharge relation (rating curve) of such shape that it can be extrapolated to peak stages without serious error.
4. The shape of the control structure should be such that the passage of water creates no undesirable disturbances in the channel upstream or downstream from the control.

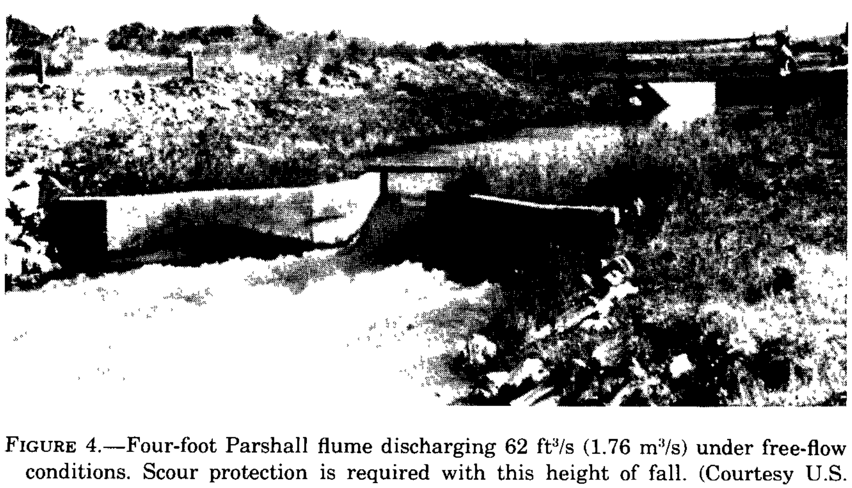

FIGURE 4.—Four-foot Parshall flume discharging 62 ft^3/s (1.76 m^3/s) under free-flow conditions. Scour protection is required with this height of fall. (Courtesy U.S. Bureau of Reclamation.)

5. If the stream carries a heavy sediment load, the artificial control should be designed to be self-cleaning. Flumes have that attribute; broad-crested weirs can often be made self-cleaning by a design modification in which the vertical upstream face of the weir is replaced by an upstream apron that slopes gently from the streambed to the weir crest.

Artificial controls are often built in conformance with the dimensions of laboratory-rated or field-rated weirs or flumes. The question arises whether to use the precalibrated rating or to calibrate in place each new installation. There are two schools of thought on the subject. In many countries, the precalibrated rating is accepted, and discharge measurements by current meter or by other means are made only periodically to determine if any statistically significant changes in the rating have occurred. If a change is detected, the new rating is defined by as many discharge measurements as are deemed neces-

FIGURE 5.—Flow through a 3-ft trapezoidal supercritical-flow flume showing transition from subcritical to supercritical flow.

sary. In other countries, including the U.S.A., the position is taken that it is seldom desirable to accept the rating curve prepared for the model structure without checking the entire rating of the prototype structure in the field by current-meter measurements, or by other methods of measuring discharge. The experience in the U.S.A. and elsewhere has been that differences between model and prototype invariably exist, if only in approach-channel conditions, and these differences are sufficient to require complete in place calibration of the prototype structure. In place calibration is sometimes dispensed with where the artificial control is a standard thin-plate weir having negligible velocity of approach.

CHOICE OF AN ARTIFICIAL CONTROL

Cost is usually the major factor in deciding whether or not an artificial control is to be built to replace an inferior natural control. The cost of the structure is affected most by the width of the stream and by the type or condition of bed and bank material. Stream width governs the size of the structure, and bed and bank material govern the type of construction that must be used to minimize leakage under and around the structure.

If an artificial control is to be used, the type and shape of the structure to be built is dependent upon channel characteristics, flow conditions, range of discharge to be gaged, sensitivity desired, and the maximum allowable head loss (backwater).

FIGURE 6.—Concrete artificial control on Mill Creek near Coshocton, Ohio.

CHOICE BETWEEN WEIR AND FLUME

As a general rule a weir is more advantageous for use as a control structure than a flume for the following reasons.

1. Weirs are usually cheaper to build than flumes.
2. A weir can be designed to have greater sensitivity at low flows with less sacrifice of range of discharge that can be accommodated, than is possible with a flume. Sensitivity is increased for a weir by notching the crest or by shaping the longitudinal profile of the crest in the form of a flat V or catenary. Sensitivity at low flow for a flume is usually attained by narrowing the effective width (converging sidewalls), or by using a trapezoidal cross section (narrower width at low stages), or by doing both; those measures significantly reduce the capacity of the flume.
3. The high water end of the stage-discharge relation for a weir can be extended beyond the stages at which the weir is effective as a control, with more confidence than can be done for a flume. In other words the stage-discharge relation for a flume becomes completely uncertain when any part of the structure upstream from the stage-measurement site is overtopped; the stage-discharge relation for a weir becomes completely uncertain only when the bank or abutment is overtopped and flow occurs around the end(s) of the weir.

If a flume is installed with the expectation that it will be overtop-

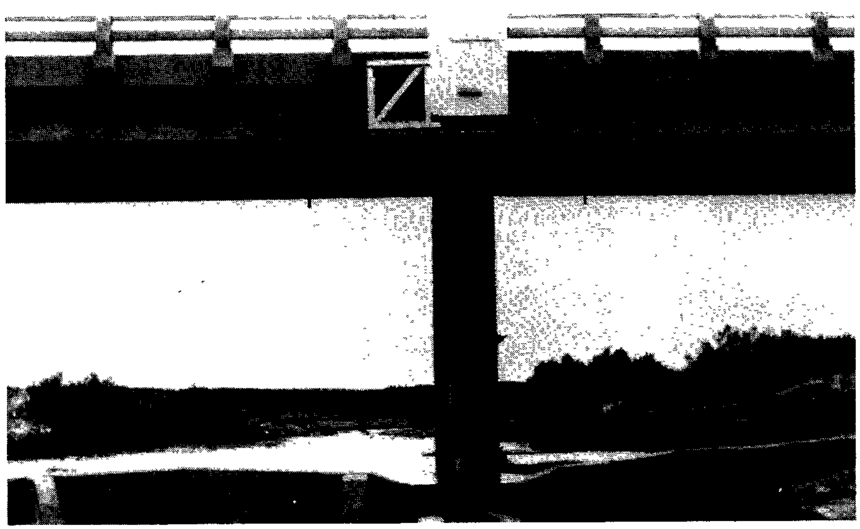

FIGURE 7.—Artificial control on Delaware River near Red Bluff, New Mex., with shallow V notch in the broad-crested weir.

ped by floodflows, it is advisable to install a nonrecording stage gage in a straight reach of channel, upstream or downstream from the flume but beyond the influence of the flume structure. Simultaneous observations of stage at the flume and in the unobstructed channel can be used to obtain a relation between the two stage gages. A stage-discharge relation for the site of the nonrecording gage can thus be derived from the flume rating, up to the discharge at which overflow starts at the flume. If for some reason, such as one of those discussed on page 273, high-flow discharge measurements are not available, the stage-discharge relation for the nonrecording gage can be extrapolated to flood stages; that extrapolation can then be used with the stage relation to define the overflow portion of the discharge rating for the flume.

However, in the following situations the use of a flume is more advantageous than the use of a weir.

1. If a heavy sediment load is carried by the stream, a weir will trap the sediment; accumulation of the sediment in the approach reach will alter the stage-discharge relation by changing the velocity of approach. Flumes however are usually self cleaning by virtue of their converging sidewalls and (or) steep floor. They therefore are more likely to maintain an unchanging stage-discharge relation. However, if the size of the sediment is not large, it is often possible to make a broad-crested weir self cleaning by including in its design an upstream apron that slopes downward from crest. An apron slope of 1 vertical to 5 horizontal will usually result in the transport of small sediment over the weir.
2. Weirs are usually not suitable for use in steep channels where the Froude number ($V/\sqrt{gd}$) is greater than about 0.75. Best results are obtained with weirs where the velocity head is a very minor part of the total head, and that is not the case in steep channels where the velocity head becomes excessively large. Furthermore, as explained above, weirs act as sediment traps on steep streams.
3. Flumes create less backwater for a given discharge than do weirs. Consequently it is more advantageous to use a flume if the channel has low banks. However for most natural streams it is impractical to design any type of structure to act solely as a metering device for the entire range of stage that may be experienced. In other words, for most natural streams sporadic overbank flooding is to be expected, with or without a control structure in the stream. Consequently the advantage of reduced backwater for a flume is usually realized only where the flow can be controlled to give some preassigned value of maximum dis-

charge. That situation occurs only in diversion canals or in natural streams having a bypass floodway.

CHOICE BETWEEN CRITICAL-FLOW FLUME AND SUPERCRITICAL-FLOW FLUME

After it has been decided for a particular site that the use of a flume is more desirable than the use of a weir, a decision must be made as to whether to use a critical-flow flume or a supercritical-flow flume.

Both types of flume will transport debris of considerable size without deposition in the structure, but if the transported rocks are excessively large, they may be deposited at or immediately upstream from the critical-depth section of a critical-flow flume. That will cause a change in the discharge rating of the flume. Therefore where that situation is likely to occur, a supercritical-flow flume should be selected for use.

If a critical-flow flume will pass the transported sediment load, that type of flume should be selected for use because the discharge rating for a critical-flow flume is more sensitive than that for a supercritical-flow flume.

SUMMARY

The artificial controls recommended for natural streams are as follows:

Sediment-transport characteristics	*Recommended structure*
Light load, small-size sediment	Weir.
Medium load, medium-size sediment	Parshall flume.
Heavy load, large-size sediment	Trapezoidal supercritical-flow flume.

The adjectives used above—light, medium, heavy, small, and large—are relative. Observation of both the study site and of the operation of control structures installed in an environment similar to that of the study site will provide the principle basis for the selection of the optimum type of control for use. In short, do not use a flume where a weir will do; if the use of a flume is indicated, do not use a supercritical-flow flume where a critical-flow flume (Parshall flume) will do.

The above recommendations also apply to canals or natural channels whose flow is controlled to limit the maximum discharge to some preassigned value. However, there is one exception; if the banks have little freeboard at the maximum discharge before the installation of an artificial control, a flume installation is generally preferable to a weir, in order to minimize the backwater caused by the structure.

DESIGN OF AN ARTIFICIAL CONTROL

Having decided on the type of artifical control to be used—weir, Parshall flume, or trapezoidal supercritical-flow flume—the next step is to design the structure. A standard design will usually be used, although channel conditions may make it necessary to make minor modification of the standard dimensions of the structure selected. The four factors—channel characteristics, range of discharge to be gaged, sensitivity desired, and maximum allowable head loss (backwater)—must be considered simultaneously in the precise determination of the shape, dimensions, and crest elevation of the control structure. However, two preliminary steps are necessary.

First, the head-discharge relations for various artificial controls of standard shape and of the type selected are assembled. Several such relations are to be found in hydraulics handbooks (King and Brater, 1963; World Meterological Organization, 1971). In addition, head-discharge relations for artificial controls that were field calibrated will usually be available in the files of water-resources agencies in the area—some are given in chapter 10. The head-discharge relations that are assembled need only be approximately correct, because channel conditions at the site of the proposed control will seldom match those for the model control.

The second preliminary step is to determine an approximate stage-discharge relation for the anticipated range in stage in the unobstructed channel at the site of the proposed control. That may be done by the use of an open-channel discharge equation, such as the Manning equation, in which uniform flow is assumed for the site and a value of the roughness coefficient is estimated. The reliability of the computed stage-discharge relation will be improved if one or more discharge measurements are made to verify the value of the roughness coefficient used in the computations. The purpose of the computations is to determine the tailwater elevation that is applicable to any given discharge after an artificial control is installed.

The next step is to consider the lower discharges that will be gaged. The tailwater elevations corresponding to those discharges are used to determine the minimum crest elevation permissible for the proposed artificial control at the lower discharges, under conditions of free flow or allowable percentage of submergence. If a flume is to be installed, the throat section should be narrow enough to ensure sensitivity at low discharges. If a weir is to be installed and the stream is of such width that a horizontal crest will be insensitive at low discharges, the use of a flat V crest is recommended—for example, one whose sides have a slope of 1 vertical to 10 horizontal. The sensitivity desired is usually such that the discharge changes no more than 2 percent for each change in stage of 0.01 ft (0.003 m). For a weir or critical-flow flume (Parshall flume) it is also desirable that the minimum discharge to be gaged have a head of at least 0.2 ft (0.06 m) to eliminate the effects of surface tension and viscosity.

Stage-discharge relations for the several controls under consideration are next prepared for the anticipated range in discharge. A structure is then selected that best meets the demands of the site in acting as a control for as much of the range as possible, without exceeding the maximum allowable backwater (head loss) at the higher stages and with minor submergence effect and acceptable sensitivity at lower stages. In other words, a high crest elevation minimizes submergence but maximizes backwater effect which may cause or aggravate flooding; a low crest elevation maximizes submergence but minimizes backwater effect; and where flumes are concerned, the attainment of the desired range of discharge may require some sacrifice of sensitivity at extremely low discharges. The engineer must use judgment in selecting a control design that is optimum for the local conditions. For example, to design a flume whose throat is sufficiently wide to accommodate the desired range of discharge, it may be necessary to relax the 2-percent sensitivity criterion at extremely low flows; in that situation the engineer may accept a sensitivity such that a change in stage of 0.01 ft (0.003 m) results in as much as a 5-percent change in discharge.

From a practical viewpoint the use of artificial controls is limited to streams with stable channels. Artificial controls seldom operate satisfactorily in sand channels having highly mobile beds. The transport of sediment as bedload continually changes the characteristics of the approach channel, and the control itself may be buried or partially buried by the movement of sand dunes.

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